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WEAPONS ACTIVITIES
of
LOS ALAMOS SCIENTIFIC LABORATORY
PART II (U)

by

Samuel Glasstone

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CONTENTS

Chapter 8

Thermonuclear Devices

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8.1 Introduction

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Thermonuclear Burning

As seen in the preceding chapters, thermonuclear (D-D and D-T) reactions are used for the initiation and the boosting of nuclear fission chains.

The problem to be considered in this chapter is the development of methods whereby large amounts of energy may be produced from thermonuclear reactions.

The continuous release of energy in a thermonuclear system involves the propagation of a chain reaction; but this resembles a thermal chain, such as occurs in flame propagation, rather than a fission chain. In the latter, particles, i.e., neutrons, produced in one step of the reaction are the means for causing further (fission) reaction to occur. In a thermonuclear system, as in a flame, the energy liberated in the reaction raises a volume element to a high temperature. This heats an adjacent volume element sufficiently to permit the reaction to occur rapidly. The resulting increase of temperature then heats a further volume element, and so on, until the reaction (or flame) has spread throughout the whole system. It is this similarity between thermonuclear reactions and flame propagation that gives rise to the use of the term "burning" in the former case (see Section 1.6), as in the latter.

It should be noted that whether burning, i.e., propagation of the reactions, will occur or not, depends on a competition between the rate at which heat is produced by the reactions and that at which it is lost, from a given volume element, in various ways. The former must, of course, predominate if burning is to occur, and the temperature attained must be high enough for the reactions to be rapid.

Material and Radiation Energies

At temperatures of the order of a few thousand degrees, the energy of a system is almost entirely material energy, i.e., essentially thermal kinetic energy with perhaps a small amount of potential energy. This material energy, E_m, is proportional, approximately, to the mass, M, of the system and to its absolute temperature, T; thus,

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$$E_m = aMT \,, \qquad (8.1)$$

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where a may, for the present purpose, be regarded as constant for the given system.

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8.2 Thermonuclear Reaction Rates

Barrier Penetration

In order for two nuclei to react, they must approach sufficiently near to one another to permit the short-range nuclear (attractive) forces to become effective. This approach will be prevented by the electrostatic (coulomb) repulsion between the positively charged nuclei. In other words, there is a potential barrier which must be overcome before the nuclei are close enough to interact. If r is the distance between the nuclei, then the height of the barrier at this point is equal to the coulombic energy, $ZZ'e^2/r$; Z and Z' are the respective nuclear

*For the basis of expressing absolute temperatures in energy (kev) units, see below.

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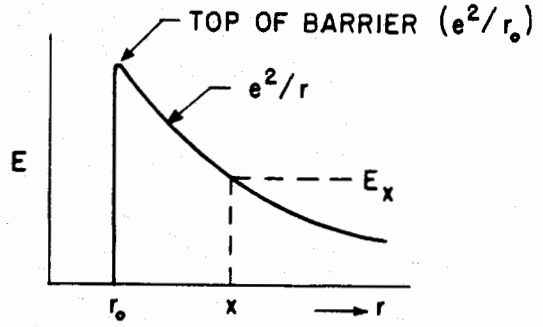

Fig. 8.1

charges and e is the unit (electronic) charge. Since Z and Z' are both unity for reactions between the isotopes of hydrogen, it is evident that these reactions involve lower potential barriers, and should occur more readily, than other nuclear reactions.

The potential barrier opposing the approach of two hydrogen nuclei is indicated in Fig. 8.1, in which the potential energy, E, equal to e^2/r, is plotted against the distance of approach of the nuclei. The potential energy is seen to drop sharply when the internuclear distance is r_o, for at this point the short-range attractive forces between the nuclei become effective. According to classical theory, therefore, the energy required to make nuclear reaction possible is equal to e^2/r_o, the potential energy at the top of the barrier.

As stated in Section 1.6, the energy e^2/r_o is of the order of 0.1 Mev; yet reactions between nuclei of hydrogen isotopes occur at appreciable rates at much lower energies. This fact has been explained by means of wave mechanics. According to classical theory, if the (kinetic) energy of a pair of nuclei is E_x (Fig. 8.1), they can approach no closer than a distance x. That is to say, they should be unable to come close enough to interact.

In terms of the wave mechanical concept, however, it can be shown that even though the energy is less than e^2/r_o, there is always a certain probability that the barrier will be penetrated and the nuclei will react. This probability is less the lower the nuclear energy, but it is, nevertheless, always finite, even though it may be very small. Consequently, nuclear reactions can occur at energies considerably less than that of the top of the potential barrier.

It may be noted that the probability of penetrating the potential barrier is greater for nuclei of low charge. This is another reason why reactions among isotopic hydrogen nuclei take place at lower energies than do those between nuclei of higher charge.

Of the reactions between pairs of nuclei of the three hydrogen isotopes, i.e., hydrogen ($_1H^1$), deuterium ($_1D^2$), and tritium ($_1T^3$), those involving H nuclei (or protons) are not important, mainly because the effective rates (or cross sections) of these reactions are relatively small.

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$$D^2 + D^2 \rightleftharpoons \begin{cases} He^3 + n^1 + 3.27 \text{ Mev} \\ T^3 + H^1 + 4.04 \text{ Mev} \end{cases}$$

$$D^2 + T^3 \longrightarrow He^4 + n^1 + 17.6 \text{ Mev}.$$

It is seen that there are two alternative D-D reactions; they take place roughly at the same rates, so that each may be regarded as occurring in half the D-D interactions.

D-D and D-T Cross Sections

The rate of a nuclear process is usually expressed in terms of the effective area per nucleus, i.e., the cross section. These cross sections can be determined experimentally by accelerating deuterons or tritons to known energies and determining the extent of interaction with other (stationary) nuclei. The results obtained for the second of the D-D reactions given above, represented by DD_p, and for the D-T reaction are shown in Fig. 8.2. The values for the other D-D reaction are very similar. The cross sections, $\sigma(E)$, are expressed in barns, i.e., in units of 10^{-24} cm^2, as a function of the deuteron energy in kev.

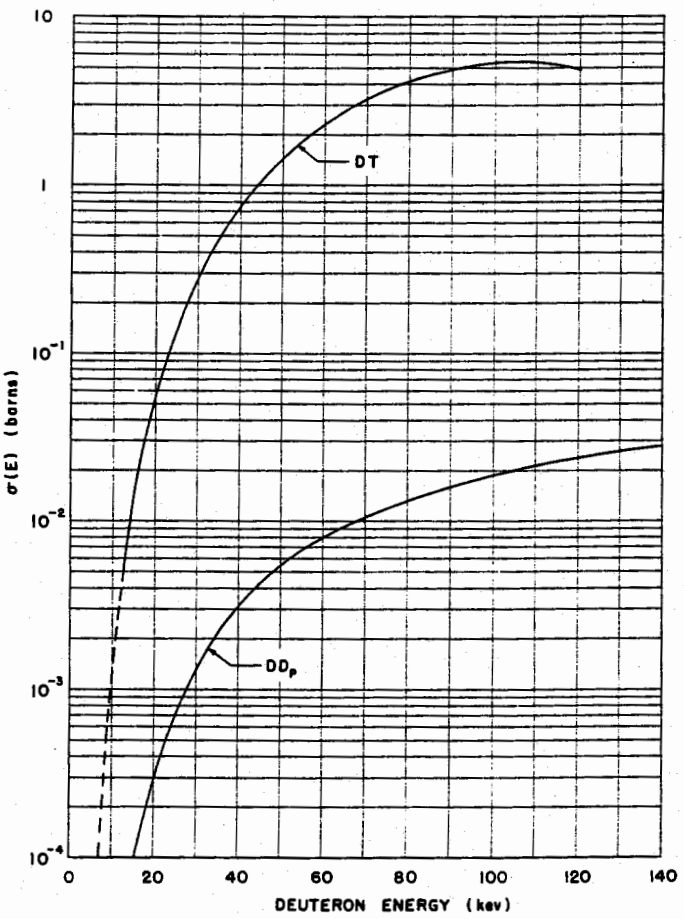

Fig. 8.2

The cross section, or reaction rate, is seen to increase with the energy, due to the increased probability of penetration of the potential barrier. It may be mentioned that the cross-section curve for the D-T reaction is not only somewhat higher than expected, but it also exhibits a maximum at energies around 100 kev (see Fig. 8.2). This is attributed to the phenomenon of resonance.

Calculation of Reaction Rates

Consider a quantity of deuterium, and let the cross section, σ, represent the effective area of a nucleus of a given energy for the D-D reaction. If v is the velocity of the deuterium nucleus, then it will sweep out an effective volume σv in unit time, e.g., per sec. If there are N deuterons per cm^3, then the total effective volume swept out is σvN per cm^3 per sec. Since there are N deuterons present per cm^3, the number of effective D-D collisions, i.e., the rate of the D-D reaction, is equal to $\sigma vN^2/2$ per cm^3 per sec. The factor of one half is introduced here, for otherwise each D-D collision is counted twice. In the case of the D-T reaction, the corresponding rate would be σvN_dN_t per cm^3 per sec, where N_d and N_t are the numbers of deuterons and tritons, respectively, per unit volume.

It is seen from the foregoing argument that, apart from the density of the material, i.e., the number of nuclei per cm^3, the rate of a nuclear reaction is determined by the product σv. In a system at a given temperature, T, not all the nuclei will have the same energy and, hence, velocity.* The energies will, in fact, be distributed over a large range from very small to very large, as indicated qualitatively, in Fig. 8.3; $n(E)/n$ is the fraction of nuclei having energy E, per unit energy interval. If the energy distribution follows the Maxwell law, then the energy corresponding to the most probable velocity, per unit velocity interval, is equal to kT, where k is Boltzmann's constant; this is generally referred to as the energy corresponding to the temperature T.

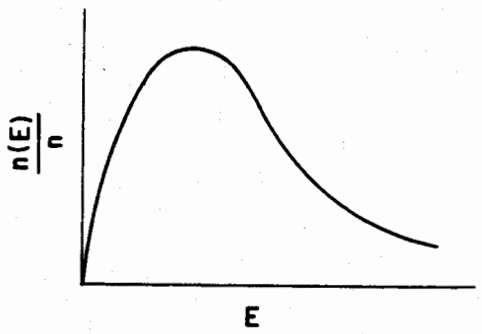

Fig. 8.3

As implied earlier, it has become the practice in the thermonuclear field to state the temperature as the energy kT, usually expressed in kev. Since k is 8.62×10^{-8} kev per degree, it follows that

$$\text{Temperature in kev} = 8.62 \times 10^{-8}\ T\ ,$$

where T is the absolute (Kelvin) temperature. Thus, a so-called temperature of 1 kev would correspond to a Kelvin temperature of 1.16×10^7 degrees.

*Since the energy E is kinetic, it is equal to $1/2\ mv^2$, where m is the mass of the nucleus; hence, v is determined by E, for a given species.

In order to determine the rate of a nuclear reaction at a given temperature, it is necessary to obtain a proper weighted average of σv, i.e., $\overline{\sigma v}$, over the whole energy range, since both σ and v vary with the nuclear energy. This can best be done by taking the experimental values of σ as a function of E (or of v), from Fig. 8.2, multiplying by the corresponding velocity, v, and then weighting each product according to the Maxwellian probability of that velocity. This operation may be expressed analytically by

$$\overline{\sigma v} = \frac{\int [\sigma(v)v] \; v^2 e^{-\frac{mv^2}{2kT}} \, dv}{\int v^2 e^{-\frac{mv^2}{2kT}} \, dv} , \qquad (8.5)$$

where the integrand in the denominator is the Maxwell factor. The values of $\overline{\sigma v}$ for one of the D-D reactions and for the D-T reaction, obtained somewhat in this manner, are plotted in Fig. 8.4 as a function of the temperature in kev. It is seen that, under equivalent density conditions, the D-T reaction is of the order of 50 to 100 times as fast as each of the D-D reactions at the same temperatures, at least in the range from 1 to 100 kev.

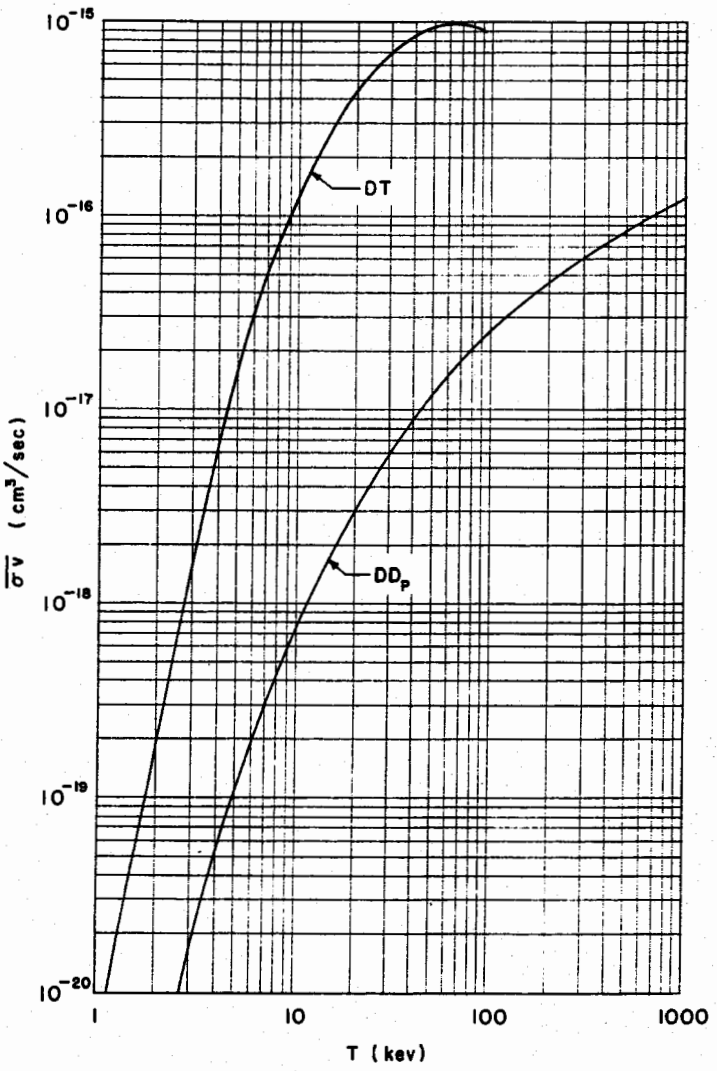

Fig. 8.4

The Reproduction Time

To illustrate the use of the data in Fig. 8.4, the energy reproduction time, i.e., the time required for the energy to double itself, in deuterium will be calculated. In every effective D-D collision, two deuterons are consumed, but in (roughly) half of these reactions a tritium nucleus is produced, which rapidly undergoes the D-T interaction with another deuterium nucleus. Thus, on the average, 2.5 deuterons are used up in every

effective collision.* From the arguments presented above, the number of effective D-D collisions is $\overline{\sigma v} N^2/2$ per cm^3 per sec, and so deuterons are consumed at the rate of $2.5\ \overline{\sigma v} N^2/2$ per cm^3 per sec. Since N is the number of deuterons present per cm^3, the fraction, F_t, of the deuterium reacting in time t sec is given by

$$F_t = \frac{2.5}{N}\ \overline{\sigma v}\ \frac{N^2}{2}\ t = 1.25\ \overline{\sigma v} N t\ , \qquad (8.6)$$

where t is assumed to be so short that N does not decrease appreciably.

If the two D-D reactions take place to, approximately, the same extent and every tritium nucleus formed rapidly undergoes the D-T reaction with another deuteron, the total energy liberated will be 4.04 + 3.27 + 17.6 = 24.9 Mev or, roughly, 25 Mev, for the consumption of five deuterons, i.e., 5 Mev or 5000 kev per deuteron. The energy ΔE produced in time t, per deuteron present in the system, is equal to F_t x 5000 kev, and so

$$\Delta E = 6250\ \overline{\sigma v} N t \text{ kev per deuteron.}$$

If E_{tot} is the total energy per deuteron present in the system, then the reproduction time, t_{rep}, i.e., the time required for the energy to double itself, due to the D-D and D-T reactions, is given by

$$t_{rep} = \frac{E_{tot}}{6250\ \overline{\sigma v} N}\ . \qquad (8.7)$$

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Production of Lithium-6

The enrichment of lithium-6, from its normal isotopic proportion of 7.3 per cent to the 95 per cent or so desirable for thermonuclear devices, is carried out by a chemical, isotopic exchange process. Lithium amalgam, consisting of a solution of metallic lithium in mercury, is allowed to interact with an aqueous solution of lithium hydroxide in water. As a result of the exchange between the lithium isotopes in the mercury and those present as ions in the water, the ratio of lithium-6 to lithium-7, at equilibrium, is larger in the amalgam than in the aqueous solution. The separation coefficient is not much greater than unity, and appreciable enrichment is achieved by a continuous counter-current process. The lithium amalgam, flowing in one direction, becomes steadily richer in the Li^6 isotope, whereas the proportion of lithium-7 increases in the hydroxide solution. Because of the separation difficulties, highly enriched lithium-6 is still rare and costly.

8.6 Thermonuclear Tests

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